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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

DOWNHOLE NMR PROCESSING

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BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention is related to methods for acquiring and processing nuclear magnetic resonance (NMR) measurements for determination of longitudinal and transverse relaxation times T_1 and T_2 . Specifically, the invention deals with use of an expert system downhole for acquiring and evaluating NMR measurements contemporaneous with the drilling of wells and with use of a downlink communication from the surface for modifying the parameters of the downhole acquisition system.

2. Description of the Related Art

[0002] Nuclear magnetic resonance is used in the oil industry, among others, and particularly in certain oil well logging tools. NMR instruments may be used for determining, among other things, the fractional volume of pore space and the fractional volume of mobile fluid filling the pore space of earth formations. Methods of using NMR measurements for determining the fractional volume of pore space and the fractional volume of mobile fluids are described, for example, in "Spin Echo Magnetic Resonance Logging: Porosity and Free Fluid Index Determination," M. N. Miller et al., Society of Petroleum Engineers paper no. 20561, Richardson, Tex., 1990. Further description is provided in U.S. Pat. No. 5,585,720, of Carl M. Edwards, issued Dec. 17, 1996 and having the same assignee as the present application, entitled "Signal Processing Method For Multiexponentially Decaying Signals And Applications To Nuclear Magnetic Resonance Well Logging Tools." The disclosure of that patent is incorporated herein by reference.

[0003] Deriving accurate transverse relaxation time T_2 relaxation spectra from nuclear magnetic resonance (NMR) data from logging subterranean formations, or from cores from such formations, is critical to determining total and effective porosities, irreducible water saturations, and permeabilities of the formations. U.S. Patent 6,069,477 to *Chen et al* having the same assignee as the present application discusses the constituents of a fluid saturated rock and various porosities of interest. Referring to **Fig. 1**, the solid portion of the rock is made up of two components, the rock matrix and dry clay. The total porosity as measured by a density logging tool is the difference between the total volume and the solid portion. The total porosity includes clay-bound water, capillary bound water, movable water and hydrocarbons. The effective porosity, a quantity of interest to production engineers is the sum of the last three components and does not include the clay bound water. Accurate spectra are also essential to estimate T_2 cutoff values and to obtain coefficients for the film model or Spectral Bulk Volume Irreducible (SBVI) model. Effective porosities are typically summations of partial porosities; however, distortion of partial porosity distributions has been commonly observed for a variety of reasons. These reasons include poor signal-to-noise ratio (SNR), and poor resolution in the time domain of the NMR data.

[0004] The most common NMR log acquisition and core measurement method employs T_2 measurements using CPMG (Carr, Purcell, Meiboom and Gill) sequence, as taught by Meiboom and Gill in "Modified Spin-Echo Method for Measuring Nuclear Relaxation Time," Rev. Sci. Instrum. 1958, 29, pp. 688-691. In this method, the echo data in any given echo train are collected at a fixed time interval, the interecho time (TE). Usually, a

few hundred to a few thousand echoes are acquired to sample relaxation decay.

However, for determination of CBW, echo sequences of as few as ten have been used.

[0005] There are numerous examples of wireline NMR logging tools used for obtaining
5 information about earth formations and fluids after a wellbore has been drilled. The
logging tools are lowered into the borehole and NMR signals are obtained using different
configurations of magnets, transmitter coils and receiver coils. Rig time is expensive, so
that the general objective in wireline logging is to obtain interpretable data within as
short a time as possible. Depending upon the reservoir, different radio frequency (RF)
10 pulsing schemes for generating RF fields in the formation have been used. The most
commonly used pulsing schemes are variations of the CPMG sequence. The parameters
that may be varied are the wait time, the number of pulses within a CPMG sequence, and
the time interval between the pulses. Long wait times are needed for proper evaluation
of the long relaxation times of gas reservoirs while short wait times and/or short pulse
15 spacings are used for evaluating clay bound water (CBW). For example, co-pending US
Patent application Ser. No. 09/396,286 (now US Patent *****) of *Thern et al*,
having the same assignee as the present application and the contents of which are fully
incorporated herein by reference, discusses the use of a dual wait time acquisition for
determination of gas saturation in a formation. US Patent 5 023 551 to *Kleinberg et al*
20 discusses the use of CPMG sequences in well logging. US Patent 6 069 477 to *Chen et*
al, the contents of which are fully incorporated herein by reference, teaches the use of
pulse sequences with different pulse spacings to determine CBW. Phase alternated pairs
(PAPs) of sequences are commonly acquired to reduce the effects of ringing.

[0006] Tool vibration is usually not a problem in wireline logging, so that data may be acquired using continuous pulsing while the logging tool is being pulled up the borehole. In many instances, other logs may already have been run before the NMR measurements are made, so that some preliminary evaluation of the subsurface formations may already exist. This makes it possible to use predefined pulse sequences optimized for specific evaluation objectives.

[0007] The commonly used seven conductor wireline is not a serious limitation to two-way communication from the surface to the logging tool. This makes it possible to process data uphole with little or no downhole processing and to send instructions downhole to the logging tool to modify the acquisition schemes based on the surface processing.

[0008] In contrast, measurements made with a drilling assembly in the wellbore have several problems. First of all, there is little prior information available about the actual subsurface formations except that inferred from surface seismic data. As would be known to those versed in the art, the resolution of such seismic data is of the order of several meters to tens of meters. This makes it difficult, if not impossible, to base an acquisition scheme on the basis of expected properties of formations.

[0009] Secondly, when the drilling assembly is in a borehole, data communication capability is in most cases severely limited. Telemetry is accomplished either by sending acoustic pulses through the mud or through the drillstring. The data rate with mud

pulsing is limited to a few bits per second and communication through the drillstring becomes a serious problem when the drillbit is being operated due to the vibration and noise produced. This makes it impossible to evaluate acquired data at the surface and to modify the acquisition scheme based on this evaluation.

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[0010] A third problem arises from the nature of NMR data itself. The sensitive volume of commonly used logging tools is no more than a few millimeters in thickness. The RF frequency is tuned to operate at the Larmor frequency corresponding to the static magnetic field in the sensitive volume, so that any transversal motion of the tool during drilling will mean that the RF pulses have a frequency corresponding to a region that has not been pre-polarized by the static magnetic field. This results in a severe degradation of the data. US Patent 5,705,927 issued to *Kleinberg* discloses making the length of each CPMG sequence small, e.g. 10 ms, so that the drill collar cannot be displaced by a significant fraction of the vertical or radial extent of the sensitive region during a CPMG pulse sequence. However using such short sequences and short wait times only gives an indication of the bound fluid volume and gives no indication of the total fluid volume.

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[0011] There is a need for an apparatus and method of obtaining NMR measurements while a wellbore is being drilled that is able to modify the acquisition parameters with a minimum of communication with the surface. Such an invention should preferably be able to adjust the acquisition depending upon actual downhole conditions. The method should preferably be robust in the presence of vibration of the logging tool. The present method satisfies this need.

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SUMMARY OF THE INVENTION

[0012] The present invention is an apparatus and method for acquiring NMR data of an earth formation using a sensor assembly conveyed on a measurement while drilling device in a borehole in the earth formation. The sensor assembly includes components on a non-rotating sleeve that may be clamped to the formation. With this arrangement, it is possible to continue drilling operations ("making hole") while making NMR pulse echo measurements at a fixed depth in the borehole and substantially isolated from vibrations caused by drilling. A downhole processor controls the acquisition and processing of the data. The processor controls the acquisition parameters based upon downhole motion sensors and also based upon control signals sent from the surface. Motion sensors such as accelerometers are used to monitor the motion of the sensor assembly and Quality control diagnostics are generated in real time. The processing includes standard processing methods. The basic pulse sequence is a CPMG sequence, although modified CPMG sequences with reduced power consumption may be employed.

[0013] An expert system in the downhole processor also determines the lithology and fluid content of formations being drilled based on signals from other formation evaluation sensors such as gamma ray, neutron, resistivity and acoustic sensors .

Information from a formation pressure tester (FPT) may also be used. The FPT provides measurements of formation pressure, mobility and compressibility of the fluid. Based upon this evaluation of the formation lithology and fluid content, the expert system may control the NMR acquisition parameters independently of surface control.

[0014] Under the control of the downhole processor, measurements may be made in one of several modes. These include measurements while the NMR sensor assembly is clamped, measurements made when the NMR sensor assembly is rotating, measurements made when connecting (adding or removing drill segments at the surface) and measurements made while tripping (pulling the drillstring out of the borehole).

[0015] The parameters of the pulse sequence that may be controlled include the wait time, the number of echos in a phase alternated pulse sequence, the number of repetitions of the phase alternated sequence, the tipping angle of the refocusing pulses, and the interecho spacing. Motion triggered pulsing may be used. In addition, the shape and bandwidth of the refocusing pulses may also be changed dynamically.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 shows the different constituents of a fluid filled rock.

FIG. 2 shows the arrangement of a measurement-while-drilling system in accordance with the present invention.

FIG 3 shows a cross section of a drilling assembly including a sensor assembly in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Fig. 2 shows a schematic diagram of a drilling system 10 with a drillstring 20 carrying a drilling assembly 90 (also referred to as the bottom hole assembly, or "BHA")

conveyed in a "wellbore" or "borehole" 26 for drilling the wellbore. The drilling system 10 includes a conventional derrick 11 erected on a floor 12 which supports a rotary table 14 that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drillstring 20 includes a tubing such as a drill pipe 22 or a coiled-tubing extending downward from the surface into the borehole 26. The drillstring 20 is pushed into the wellbore 26 when a drill pipe 22 is used as the tubing. For coiled-tubing applications, a tubing injector, such as an injector (not shown), however, is used to move the tubing from a source thereof, such as a reel (not shown), to the wellbore 26. The drill bit 50 attached to the end of the drillstring breaks up the geological formations when it is rotated to drill the borehole 26. If a drill pipe 22 is used, the drillstring 20 is coupled to a drawworks 30 via a Kelly joint 21, swivel, 28 and line 29 through a pulley 23. During drilling operations, the drawworks 30 is operated to control the weight on bit, which is an important parameter that affects the rate of penetration. The operation of the drawworks is well known in the art and is thus not described in detail herein.

[0018] During drilling operations, a suitable drilling fluid 31 from a mud pit (source) 32 is circulated under pressure through a channel in the drillstring 20 by a mud pump 34. The drilling fluid passes from the mud pump 34 into the drillstring 20 via a desurger 36, fluid line 28 and Kelly joint 21. The drilling fluid 31 is discharged at the borehole bottom 51 through an opening in the drill bit 50. The drilling fluid 31 circulates uphole through the annular space 27 between the drillstring 20 and the borehole 26 and returns to the mud pit 32 via a return line 35. The drilling fluid acts to lubricate the drill bit 50 and

to carry borehole cutting or chips away from the drill bit 50. A sensor S_1 preferably placed in the line 38 provides information about the fluid flow rate. A surface torque sensor S_2 and a sensor S_3 associated with the drillstring 20 respectively provide information about the torque and rotational speed of the drillstring. Additionally, a
5 sensor (not shown) associated with line 29 is used to provide the hook load of the drillstring 20.

[0019] In one embodiment of the invention, the drill bit 50 is rotated by only rotating the drill pipe 22. In another embodiment of the invention, a downhole motor 55 (mud motor)
10 is disposed in the drilling assembly 90 to rotate the drill bit 50 and the drill pipe 22 is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction.

[0020] In the preferred embodiment of Fig. 2, the mud motor 55 is coupled to the drill bit
15 50 via a drive shaft (not shown) disposed in a bearing assembly 57. The mud motor rotates the drill bit 50 when the drilling fluid 31 passes through the mud motor 55 under pressure. The bearing assembly 57 supports the radial and axial forces of the drill bit. A stabilizer 58 coupled to the bearing assembly 57 acts as a centralizer for the lowermost portion of the mud motor assembly.

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[0021] In one embodiment of the invention, a drilling sensor module 59 is placed near the drill bit 50. The drilling sensor module contains sensors, circuitry and processing

software and algorithms relating to the dynamic drilling parameters. Such parameters preferably include bit bounce, stick-slip of the drilling assembly, backward rotation, torque, shocks, borehole and annulus pressure, acceleration measurements and other measurements of the drill bit condition. A suitable telemetry or communication sub 72 using, for example, two-way telemetry, is also provided as illustrated in the drilling assembly 100. The drilling sensor module processes the sensor information and transmits it to the surface control unit 40 via the telemetry system 72.

[0022] The communication sub 72, a power unit 78 and an MWD tool 79 are all connected in tandem with the drillstring 20. Flex subs, for example, are used in connecting the MWD tool 79 in the drilling assembly 90. Such subs and tools form the bottom hole drilling assembly 90 between the drillstring 20 and the drill bit 50. The drilling assembly 90 makes various measurements including the pulsed nuclear magnetic resonance measurements while the borehole 26 is being drilled. The communication sub 72 obtains the signals and measurements and transfers the signals, using two-way telemetry, for example, to be processed on the surface. Alternatively, the signals can be processed using a downhole processor in the drilling assembly 90.

[0023] The surface control unit or processor 40 also receives signals from other downhole sensors and devices and signals from sensors S_1 - S_3 and other sensors used in the system 10 and processes such signals according to programmed instructions provided to the surface control unit 40. The surface control unit 40 displays desired drilling parameters

and other information on a display/monitor 42 utilized by an operator to control the drilling operations. The surface control unit 40 preferably includes a computer or a microprocessor-based processing system, memory for storing programs or models and data, a recorder for recording data, and other peripherals. The control unit 40 is
5 preferably adapted to activate alarms 44 when certain unsafe or undesirable operating conditions occur.

[0024] A suitable NMR device for use in the present invention is disclosed in US Patent 6,247,542 to *Kruspe et al*, the contents of which are fully incorporated herein by
10 reference. This is show in Fig. 3. A segment 70 of drill pipe 22, illustrated in greater illustrates the apparatus and method according to *Kruspe* including a sleeve member, such as a sensor assembly, slidably coupled to a longitudinal member, such as a section of drill pipe, wherein, when the sleeve member is non-rotating, the longitudinal member is free to rotate. The sleeve member may be held in a non-rotating position through
15 engagement with the borehole wall and a decoupling of the sleeve member and the rotating drillstring. However, the apparatus and method according to the present invention can be adapted for any MWD device or tool typically used on a rotating drillstring.

20 [0025] The MWD tool 79, including an associated pulsed NMR tool 77 having a sensor assembly 113, and the pulsed power unit 78 are connected in tandem in the drilling assembly 90. The MWD tool 79 may also include a sonic sensor, a density measurement

tool, and a porosity measurement tool. As seen in Fig. 3, the NMR tool 77 is rotationally symmetric about a longitudinal axis 128 of the drilling assembly 100. The longitudinal member is, for example, a drill pipe section 101, which forms the core of the segment 70. Alternatively, the longitudinal member is a shaft in a downhole directional drilling assembly. The drill pipe section 101 is connected to the drillstring 20 by the upper tool joint 103 and the lower tool joint 139, and has a channel or flow pass 105 for the drilling mud to flow downhole. The sensor assembly 113 surrounds the drill pipe section 101 and is slidably coupled to the longitudinal member or the drill pipe section 101. The sensor assembly 113 is coupled to the drill pipe section 101 by at least one of guide sleeves 109 and 111. The guide sleeves 109 and 111 include, for instance, slip rings and bearings 110 and 112, respectively. Alternatively, a single guide sleeve (not shown) including slip rings and bearings, is used, for example, centrally located between ends of the sensor assembly 113. The guide sleeves 109 and 111 allow the sensor assembly 113 to move freely in the axial direction and to a lesser extent laterally with respect to the drill pipe section 101. The sensor assembly 113 has an outer diameter that is somewhat less than the inner diameter of the borehole 26. For illustrative purposes, Fig. 3 shows the space between the sensor assembly 113 and the borehole wall in an exaggerated manner. The NMR sensor assembly includes flow paths 107 and 114 for return flow of the drilling mud from the drilling assembly 90 below wherein the gap between the sensor assembly 113 and the borehole wall are minimized.

[0026] The magnet assembly 115, for providing the static magnetic field, and the RF coil assembly 117 are disposed in the sensor assembly 113. The RF coil assembly 117 includes, for instance, at least one transmitter for transmitting a pulsed RF field into the formation. In the configuration as illustrated in Fig. 3, the RF field is axial and is orthogonal to the static field of the permanent magnet assembly 115 in a region of interest or examination outside the borehole for NMR signal measurements. However, the apparatus of the present invention is not limited to the illustrated sensor assembly 113. Any number of appropriate magnet arrangements and antenna or coil arrangements which provide a static magnetic field and an RF field orthogonal to the static magnetic field direction for creating the region of interest for NMR signal sensitivity can be used according to the present invention. For example, the NMR tool 77 can employ separate transmitter and receiver RF coils, located, for example, on the sensor assembly 113.

[0027] Typically, the RF coil assembly 117 is pulsed and creates a high frequency electromagnetic RF field orthogonal to the static magnetic field generated by the magnet assembly 115 and in the region of substantially uniform field strength creating the region or volume of interest for NMR signal sensitivity. The sensor assembly 113 detects the NMR signals resulting therefrom. Rock pores in the earth formations surrounding the wellbore are filled with fluid, typically water or hydrocarbon. The hydrogen nuclei in the fluid are aligned by the region of homogeneous magnetic field, generated by the magnet assembly 115. The hydrogen nuclei are then flipped away from the homogeneous magnetic field by the pulsed RF field produced by RF coil assembly 117. At the

termination of the pulsed RF field from RF coil assembly 117, the hydrogen nuclei
revolve or precess at high frequency around the homogeneous magnetic field inducing an
NMR signal in the RF coil assembly 117 until the hydrogen nuclei relax to the original
direction along the homogeneous magnetic field. The induced NMR signals are
5 processed downhole or sent to the surface for processing.

[0028] Those versed in the art would recognize that, depending upon the configuration of
the permanent magnet assembly 115, the region of examination could have one of a
number of configurations. In one embodiment, the region of examination could be
10 substantially toroidal shaped with the axis of the toroid along the longitudinal axis of the
tool. In other configurations, the region of examination could be localized on opposite
sides of the borehole or even on just one side of the borehole. It will also be clearly
apparent to those skilled in the art that the static magnetic field area can also be obtained
if the magnet assembly 115 includes dc-energized electromagnets, or superconducting dc
15 electromagnets. All of these are intended to be within the scope of the present invention.

[0029] The NMR electronics 129 is housed in the NMR sensor assembly 113. The
purpose of the NMR electronics 129 is to control the sensor assembly 113, record,
process and transmit the recorded data, to the telemetry module 72. This can be done by
20 means of electrical or acoustic telemetry by known devices and will not be discussed. A
spring 130 having a cable conduit through the spring 130 allows power and data
transmission via the guide sleeve 111 and slip ring through the cable conduit to and from

the MWD tool 79. The MWD tool 79 also transmits data to the sensor assembly 113, for example, through mud pulse telemetry, and provides power from the power unit 78. The NMR electronics may also be referred to hereafter as a downhole processor, though it is to be understood that a downhole processor may be located at other positions in the downhole assembly.

[0030] The sensor assembly 113 is also provided with at least one clamping pad, clamping piston or ribs 121. The ribs 121 are capable of outward movement for locking the sensor assembly 113 to the borehole wall during measurement by the sensor assembly 113. In one embodiment, the ribs 121 are hydraulically activated. In the inactivated position of the ribs 121, the sensor assembly 113 rests on the lower tool joint 139 and is held up against gravitational pull by the spring 130 that is fixedly attached to the drill pipe section 101. Continued rotation of the drillstring 20 loosely carries the sensor assembly 113 along. In the activated position, the ribs 121 engage the borehole walls and prevent any further movement of the sensor assembly 113. Further rotation of the drillstring 20 does not affect the position of the sensor assembly 113 that remains in a clamped position against the borehole wall. In the clamped position, the sensor assembly 113 is essentially decoupled from rotational and vertical movement of the drillstring 20, enabling measurements, such as NMR measurements from the NMR sensor assembly 113, to be carried out without interference from tool motion and vibration. Due to the proximity of the borehole wall to the magnet assembly 115, the region of examination is within the formation and any signal from the borehole fluid is small. In typical operation,

the NMR measurement takes between 0.01 to 1 second, during which time the drill pipe section 101 advances some distance. Once the NMR measurement has been completed, the ribs 121 are retracted, as a result of which the sensor assembly 113 is no longer coupled to the borehole wall. The sensor assembly 113 then drops down until any further
5 downward motion is stopped by the spring 130. In another embodiment, the ribs 121 are actuated electrically, e.g., by a stepper motor. Other methods, such as those using springs, would be known to those versed in the art.

[0031] The device of *Kruspe* thus comprises a sensor assembly mounted on a slidable
10 sleeve slidably coupled to a longitudinal member, such as a section of drill pipe. When the sensor assembly is held in a non-rotating position, for instance for obtaining the measurements, the longitudinal member is free to rotate and continue drilling the borehole, wherein downhole measurements can be obtained with substantially no sensor movement or vibration. This is particularly useful in making NMR measurements due to
15 their susceptibility to errors due caused by tool vibration. A clamping device is used, for instance, to hold the sensor assembly is held in the non-rotating position.

[0032] The specific NMR sensor disclosed in *Kruspe* et al has permanent magnets as well as RF antennas on the sleeve. A suitable sensor configuration is disclosed in U.S. Patent
20 6,215,304 to *Slade*, the contents of which are fully incorporated herein by reference. The tool is rotationally symmetric, i.e., it measures 360° around the tool simultaneously. However, as noted in the *Kruspe* patent, other magnet and antenna configurations could

be used. An advantage of using the *Slade* device is that usually no borehole correction is necessary because the tool is tuned to read only formation signal unless the hole is severely enlarged or the tool is off center.

5 [0033] A thruster allows compensation for the axial drillstring movement during the acquisition. This provides the tool with a great deal of flexibility in acquisition of NMR data. Specifically, four modes of operation are possible with the tool:

1. Measurement while the drillbit is actively engaged in making hole with the NMR sensor clamped to the formation;
- 10 2. Measurement while the drillbit is actively engaged in making hole with the NMR sensor rotating and moving downhole;
3. Measurement while connecting; and
4. Measurement while tripping.

For convenience, the first mode is referred to as the clamped mode, the second as the
15 rotating mode, the third as the connecting mode and the fourth as the tripping mode. It should also be noted that there are other devices besides drillbits that could be used for “making hole”, i.e., actively penetrating the formation. An example of this is the use of cutting jets that “make hole” by the use of a fluid at high pressure injected through a nozzle. The term “making hole” as used hereafter is intended to cover the use of drillbits, cutting
20 jets and other similar devices. The four modes of operation are now discussed briefly.

[0034] In the clamped mode of operation, the sensor assembly is clamped to the borehole and is thus substantially decoupled from motion of the drillbit and vibration of

the bottom hole assembly. Depending upon the rate of penetration (ROP), data acquisition in the clamped mode may be carried out for several minutes. This makes it possible to acquire data with long pulse sequences with enhanced signal to noise ratio (SNR).

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[0035] In the rotating mode, the sensor assembly is rotating at a rate that could be almost as rapid as the rotation of the drilling tubular. The rotation by itself does not degrade the quality of data acquired by the sensor assembly due to the complete rotational symmetry of the region of examination of the tool. However, due to tool vibration (transverse and vertical) and whirl, data quality may be degraded. This arises from the fact that the region of examination is relatively small so that pulse echo signals may arise from regions of the formation that are only partially polarized by the permanent magnets.

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[0036] To deal with the problems caused by tool motion in the rotating mode, one embodiment of the present invention uses the teachings of co-pending U.S. Patent Application Ser. No. 09/778,205 of *Hawkes et al*, the contents of which are incorporated herein by reference. *Hawkes et al* teach the use of motion triggered pulsing for NMR measurements. The motion of the tool is measured by suitable motion sensors, such as accelerometers, magnetometers or gyroscopes or combinations thereof. These sensors may be placed at any suitable location on the drilling tool in the proximity of the magnet and coil arrangement. The wait period in a pulse sequence may be extended slightly without affecting the data quality and this feature may be used to delay the application of the tipping pulse until a suitable state of tool motion is achieved. The trigger may be

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obtained by monitoring the motion sensor signals. Suitable states for triggering are instantaneous moments when the tool is stationary, or if the motion has a strong periodic component, then subsequent pulse sequences may be triggered to synchronize with this motion. Such motion triggered pulsing will improve the NMR spin-echo formation.

5 *Hawkes* also teaches the use of predictive filtering, such as Kalman filtering, for initiating the tipping pulse that is commonly used in a CPMG pulse sequence. This too may be used in the method of the present invention.

10 [0037] As would be recognized by those versed in the art, the length of the pulse sequences used in analysis of the formation would be controlled at least in part by the ROP. At low ROP, it is possible to use long pulse sequences to improve the SNR without loss of resolution. As always, the available power is a limitation and an optional embodiment of the present invention may use the modified CPMG sequence taught in US Patent 6 163 153 by *Reiderman* et al with a shortened refocusing pulse.

15 [0038] In the changing mode, the drillbit is non-rotating and the drillstring is clamped at the surface while additional sections of drill pipe are added or removed. However, due to the elasticity of the drillstring, vertical and transverse vibrations continue. The total acquisition time is usually limited to less than sixty seconds. Again, the motion triggered
20 pulsing scheme of *Hawkes* et al may be used, and with better results than in the rotating mode. The improvement arises from the fact that the entire drillstring may be vibrating freely without additional stresses and whirl caused as the drillbit “makes hole.”

[0039] In the tripping mode, the axial tool motion is quite rapid. Typically, three sections of drillstring (a total of 90 ft.) are pulled at a time, after which the drillstring is clamped at the surface (at which time acquisition in the changing mode is possible). Due to the rapid tool movement and the small aperture of the NMR tool, correction has to be made for the change in the sensitive volume during a pulse sequence. In one embodiment of the invention, this is a simple geometric correction factor based upon the nominal velocity of tool motion as measured at the surface. In an alternate embodiment of the invention, accelerometers on or near the NMR sensor make measurements of the axial acceleration of the NMR sensor. The actual velocity of tool motion is determined from the accelerometer measurements and used to derive the correction factor.

[0040] Regardless of the mode of operation, data are acquired and processed using one of two schemes. The standard data acquisition and processing scheme uses methods that have been used in wireline logging. The acquisition and processing parameters for this are stored in the memory of the downhole processor and are described below. In addition to the standard acquisition and processing scheme, the downhole processor also includes an expert system that analyzes data acquired by the NMR sensor assembly and one or more additional sensors, including formation sensors and sensors indicative of drilling conditions as discussed above. The expert system, as described below, modifies the acquisition and processing schemes used for the NMR data. This may be done independently of the surface processor 40 or may be done in response to downlink commands from the surface processor 40 through the communication sub 72. Such a

downlink telemetry system is taught in European Patent 744,527 of *Oppelt et al* and United States Patent 5,963,138 of *Gruenhagen et al*, having the same assignee as the present application.

5 STANDARD ACQUISITION AND PROCESSING

[0041] The acquisition and processing steps are discussed in conjunction. One pre-processing step that is routinely carried out is replacement of invalid data. Based on Quality Control (QC) diagnostics that indicate the tool performance, invalid data are recognized and (if possible) replaced by valid data. Recognition of invalid data is based
10 on adequate diagnostics. These diagnostics are provided by the motion sensors discussed in the *Hawkes* application. Even in the clamped mode of acquisition, it is preferable to do the clamping at a time when the motion of the drill collar is small. While this is not a guarantee that good data will be acquired when clamped, it does provide some insurance. When data are acquired in the rotating mode, motion triggered pulsing is highly
15 desirable. However, analysis of the data after acquisition may still require that all data of one acquisition cycle be discarded. For this purpose, diagnostics data have to be acquired and evaluated parallel to the NMR acquisition (e.g., hardware performance, vibration data). If these data are not available, the data quality can be indicated with real-time analysis of the sum of echos (SE) as discussed below.

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[0042] If the motion sensors indicate that the entire cycle of measurements made in the clamped mode is defective due to excessive motion, then no correction of the data is possible. If, however, excessive motion occurs with a single echo train out of a plurality

of echo trains made at a clamped position, then that echo train is replaced by a previously acquired echo train of the same phase and channel. The term "phase" here refers to phase alternated pulse sequences in the data acquisition as used in the art. The term "channel" refers to the fact that NMR echo signals are acquired in two channels that are in-phase and in quadrature to the RF carrier phase.

[0043] As another part of the preprocessing, if portions of echo trains are acquired when the diagnostics indicate excessive vibration, then these partial echo trains are replaced with null values. Subsequent processing recognizes these null values and accounts for them in the processing. Finally, if isolated points of the echo sequence are invalid, then these isolated points are replaced with a weighted or unweighted average of surrounding echo (point) data.

[0044] Another aspect of the present standard preprocessing in the present invention is that based on the echo shape and the overlying noise (white noise plus non-random ringing) several methods can be used for echo point averaging with different purposes. One simple method to average echo points is linear averaging of the data in the whole acquired echo window. An alternate embodiment of the invention uses weighted averaging of the data, where the weighting is fixed (e.g., cosine function) or determined in lab and field experiments (e.g., expected shape of the echo signal to maximize signal-to-noise ratio). These windows are centered on a peak value of the measured echo signal and provide some discrimination against random noise.

[0045] Another preprocessing step in the invention uses sums of individual echo trains as a quality control (QC) indicator. US Patent Application Ser. No. 09/483,336 to *Chen* discusses the use of summed echo trains as a QC indicator and is incorporated herein by reference. In the present invention, sums of individual echo trains at a clamped depth are used to determine the quality of the data.

[0046] The standard preprocessing preferably includes the so-called phase alternated pulse (PAP) sequence. Successive CPMG or modified CPMG sequences are acquired with alternating phases of the tipping pulse. Depending on the sign convention used, the -90°_x and $+90^\circ_x$ data are either subtracted or added to eliminate constant offset of the echo channel data. If different echo train data are combined (also for phase and amplitude calculation and stacking), a corrected acquisition time for the combined data has to be calculated (e.g. for PAP data calculate mean acquisition time of the two echo trains) In an alternate embodiment of the invention, no PAP averaging is done. Such a method of data acquisition and processing is taught in co-pending United States Patent application Ser. No. 09/691,514 of *Chen*, having the same assignee as the present application and the contents of which are fully incorporated herein by reference. As taught by *Chen*, phase alternation is done in the acquisition, but no averaging is done for pairs of phase alternated data; instead,

[0047] The preprocessing also includes a correction for stimulated echo effects. The stimulated echo effects arise from imperfect tipping and refocusing pulses. Even a small gradient field makes it impossible to create a perfect pulse that will rotate protons in the

sample space exactly the desired angle (e.g. 180°) and not rotate protons “near” the sample space that are off resonance. The calibration of the tool in a known environment allows these effects to be determined and correction equations derived. As a result of the imperfect pulses, the first few echoes do not fit the rest of the echoes and need to be

5 scaled by a correction factor. It is commonly observed that amplitude of the first echo has to be increased, while the amplitude of later echos (such as the second and third echos) needs to be decreased by the stimulated echo correction. The correction for the first echo varies quadratically with B_1 and is computed from the current B_1 value. The correction for the second echo is independent of B_1 . The correction equation is:

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$$EPA_{n,corr} = STE_n * EPA_n \quad (1)$$

where EPA_n and $EPA_{n,corr}$ are the uncorrected and corrected values of the n -th echo, and STE_n is the stimulated echo correction. In a preferred embodiment of the invention, STE_n is determined by lab or field experiments or by simulation results. As would be known to those versed in the art, STE_n depends upon B_1 and the operating temperature.

15 It may also depend upon the tipping and refocusing angles and the bandwidth of the transmitter and receiver.

[0048] Included in the standard preprocessing is a determination of the phase angle and noise level and correcting the measured amplitudes based on the phase angle. The

20 signals measured in the two channels E_x and E_y have amplitudes E_{xn} and E_{yn} respectively. The phase angle θ is given by

$$\theta = \tan^{-1} \left[\frac{\sum_{n=1}^{NE} E_{xn}}{\sum_{n=1}^{NE} E_{yn}} \right] \quad (2),$$

the echo amplitude E_n is given by

$$E_n = E_{yn} \cos \theta + E_{xn} \sin \theta \quad (3),$$

the noise N_n is given by:

$$5 \quad N_n = E_{xn} \cos \theta - E_{yn} \sin \theta \quad (4)$$

and the noise level σ_N is given by:

$$\sigma = \sqrt{\frac{\sum_{n=1}^{NE} (N_n - \text{mean}(N))^2}{NE - 1}} \quad (5).$$

[0049] After the preprocessing steps are carried out, additional processing of the data is carried out for determination of petrophysical parameters of the formation. As part of the petrophysical processing, a calibration is carried out. A calibration factor is used to convert measured echo signals to signal amplitudes in porosity units (p.u.). Measurements are taken in an environment with known porosity and where a single decay component of the fluid is expected. The calibration procedure includes:

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1. Measuring the temperature $Temp_{cal}$
2. Measuring echo data in a medium of known porosity ϕ_k . In a preferred embodiment of the invention, this step comprises making measurements in a calibration chamber filled with 100% water ($\phi = 1.0$).
3. Deriving a best linear fit to the logarithm of the echo data.
4. Extrapolating the linear fit back to zero time to give a value of the echo at zero time E_0 .
5. Obtaining the calibration factor C as

$$C = \phi_k / E_0. \quad (6)$$

The derived calibration factor C is applied to the acquired echo data.

[0050] Increasing salinity causes displacement of hydrogen atoms by salt ions. The salinity correction factor is multiplied to the echo data for compensation. The petrophysical processing of the echo data typically includes a correction for salinity.

The salinity of the fluid in the tool's sensitive region can be approximated by the formation fluid salinity or, in case of an invaded formation, by the salinity of the mud filtrate. No salinity correction is necessary if the formation is mainly oil filled or if the resistivity of the formation fluid $> 10 \Omega m$ at 75°F. The salinity correction SC is given by:

$$SC = NaCl / 100,000 * 0.04 + 1 \quad (7)$$

$NaCl$ = salinity of the fluid in the NMR-sensitive volume [in ppm]

[0051] Another step in the petrophysical processing is the derivation of the sum of echos SE. SE provides QC information used as discussed above in [0031]. SE also provides petrophysical information such as a high resolution permeability estimation. Such a method is disclosed in *Sezinger* et al., "High Resolution Permeability Indicator" presented at the 1999, SPWLA Annual Conferences and Exhibition, Oslo, Norway, June 1999.

[0052] Stacking of the data may be performed to increase SNR. In the clamped mode, this includes averaging of all data from one clamping cycle. In the connecting mode, this includes averaging of all data from one resting cycle. In the tripping mode, this includes windowed averaging of data over a plurality NL levels. Typically, in the tripping mode, data from up to 4 levels are averaged.

[0053] The downhole processor includes a program that determines the porosity of the formation and the irreducible water saturation (BVI). The acquired echo data are fitted by a multi-exponential decay plus an optional constant term:

$$E_n = \phi_0 + \sum_{i=1}^K \phi_i e^{-n\Delta/T_{2i}} \quad (8)$$

where n is the echo index and Δ is the interecho spacing. In a preferred embodiment of the invention, two exponential terms are used ($K=2$). In such a case, the total porosity ϕ is given by

$$\phi = \sum_{i=0}^k \phi_i \quad (9)$$

The irreducible water saturation, BVI, is calculated by weighted contributions of the partial porosities in reference to a given cutoff value, T_{2c} . Porosity can also be measured by additional sensors (e.g. density, acoustic, neutron etc.) and can be compared with those measurements on a realtime basis.

[0054] Another step in the petrophysical processing is the correction for formation temperature. The formation temperature affects the thermal relaxation of the protons for T_1 and T_2 and reduces the amplitude of the returned signal with decreasing temperature. The magnitude of the amplitude correction expressed as the Formation Temperature Multiplier, FTM, is proportional to the absolute temperature.

$$FTM = (Temp_f + 273.15) / (Temp_{ref} + 273.15) \quad (10)$$

where

$Temp_f$ = Formation temperature in °C

and $Temp_{ref}$ = Calibration reference temperature in °C. This equation is based on Curie's Law.

[0055] The increased temperature of the formation reduces the density of the formation fluid and decreases the hydrogen index. Higher pressure increases the hydrogen index. The petrophysical processing includes a compensation for this change. The net difference is compensated for by the Hydrogen Depletion Multiplier, HDM, which is a function of the apparent porosity and formation temperature.

$$\text{HDM} = (\phi_a / 30) * ((\text{Temp}_f - 10) / 194.44) * 0.1 + 1 \quad (11)$$

where ϕ_a = Apparent porosity from eq. (9), and Temp_f = Formation temperature in °C

[0056] In a preferred embodiment of the invention, when standard processing is used, the downhole processor sends processed data to the surface processor using the telemetry sub 72. Due to the limited transmission capability of the telemetry channel, the data that are sent up are limited. Typically, they include the total porosity ϕ , the BVI, the sum of echos SE, and the level σ_h . Additional QC indicators that may be sent include the signals indicative of the motion of the tool. This is in addition to other formation evaluation data that may be sent uphole. These may include processed or unprocessed data from gamma ray tools, neutron logging tools, density tools and resistivity tools. Such devices would be known to those versed in the art and are not discussed here further.

[0057] The operator at the surface has access to the data sent from the telemetry sub 72 and they are processed and/or displayed by the surface control unit 40. Based upon this, the operator can evaluate the drilling conditions, make judgments about the lithology and formation fluid being drilled and evaluate the quality of the data (specifically including

the NMR data). Based upon this evaluation, the operator may send instructions downhole that alter the acquisition parameters being used for the NMR data. This is done on a real-time basis in the drilling or clamping mode. It may also be done in the connecting mode and the tripping mode with less effectiveness. The reasons for the lowered effectiveness of altering the acquisition parameters is that in the tripping mode, the bottom hole assembly generally has a fairly rapid motion that may encompass several different lithologies and fluid types. The acquisition parameters that may be controlled are discussed next.

[0058] In a preferred embodiment of the invention, much of the NMR data are acquired using CPMG sequences or modified CPMG sequences as taught by *Reiderman* et al. As would be known to those versed in the art, a CPMG sequence may be represented as:

$$[TW_i - 90_{\pm\pi/2} - (\tau - X - \tau - echo)_j]_i \quad (12)$$

where TW is a wait time, $90_{\pm\pi/2}$ refers to a phase alternated 90° tipping pulse, X is a refocusing pulse with a tipping angle that lies between 90° and 180° , j is the number of echos observed and 2τ is an interecho spacing. The basic sequence within the square bracket may be repeated i times with different wait times and the whole sequence denoted by eq. (12) may be repeated at a single clamp position a plurality of times to improve the SNR. In the connecting and drilling modes, the number of repetitions is less than in the clamped mode. In the tripping mode, it is usually not possible to repeat the basic sequence due to the high rate of axial movement of the tool.

[0059] As noted above, data are preferably acquired using the phase alternation of the 90° tipping pulse. This is necessary to avoid baseline errors. Apart from this, the downhole processor has the capability of adjusting any of the parameters in the pulse sequence given by eq. (12). As noted above, in one embodiment of the invention, these changes are made by the operator at the surface using a downlink capability. The effects of changes in the parameters are discussed next.

[0060] The simplest parameter that may be controlled is the number of repetitions i in eq. (12). The primary use of this is to improve the SNR and make use of the stacking capability discussed above. The selection of this is determined primarily by the vibration of the tool and the accompanying degradation of the echo signals. In the clamped mode, this may be selected to be as large as necessary since there is no axial tool motion. In the connect mode, even though there is no axial movement of the drillstring at the surface, due to the elasticity of the drillstring, there may be axial movement of the NMR sensor assembly at depth. Obviously, in the tripping mode, the number of repetitions can be increased only at the cost of loss of resolution. In the drilling mode, the loss of resolution with a large choice of i depends upon the rate of penetration ROP: in hard limestones and dolomite rocks, the ROP is small and hence more repetitions can be done, while in soft shales and soft sandstones, the number of repetitions would be less.

[0061] Along with i , the wait time TW can also be changed. The effect of changing the wait time is to change the amount of polarization of the nuclear spins between successive CPMG sequences produced by the static magnetic field. In reservoirs including gas or

light oil, long wait times are required to fully polarize the hydrogen nuclei. This would appear to make it necessary to acquire data with long wait times to provide an estimate of gas saturation. In the clamped mode, wait times of several seconds are possible.

However, estimates of gas saturation may also be obtained using shorter wait times. This is discussed in copending US Patent Application Ser. No. 09/396,286 of *Thern* et al, the contents of which are fully incorporated herein by reference. *Thern* teaches the use of a dual wait time data wherein the formation water is substantially fully polarized at both wait times, while the gas component experiences a different partial saturation for the two wait times. The method of *Thern* may be used at normal logging speeds and is hence also suitable for measurements in the drilling mode and in the connect mode. It may also be used with less effectiveness in the tripping mode.

[0062] At the other end of the relaxation time distribution, clay bound water has an extremely short relaxation time. There are a number of different approaches that may be taken to address this problem. In one embodiment of the invention, a first plurality of short pulse sequences (small values of j) are acquired followed by a second plurality of longer pulse sequences (larger values of j) wherein the second plurality i is less than the first plurality i . This makes it possible to improve the SNR for the early portion of the decay spectrum that needs it the most. Alternatively, a series of short pulse sequences are acquired with a small value of τ followed by one or more regular (long) pulse sequences with a longer value of τ . The short pulse sequences with the small value of τ make it possible to determine the CBW of the formation while the long pulse sequence is used for obtaining the slowly relaxing components. In an alternate embodiment of the

invention, data are acquired with a variable τ within a single sequence as taught in an application entitled "NMR Data Acquisition with Multiple Interecho Spacing" filed under Attorney Docket No. 414-26580 on June 28, 2001, the contents of which are fully incorporated herein be reference.

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[0063] Another acquisition parameter that can be controlled is the length and shape of the refocusing pulse. The *Reiderman* patent discusses the advantage of shortening the tipping angle of the refocusing pulse for conserving power. In an alternate embodiment of the present invention, the shape of the refocusing pulse may also be changed. Co-
10 pending US Patent Application Ser. No. 09/606,998 of *Beard* et al, having the same assignee as the present application and the contents of which are fully incorporated herein by reference, discusses the effect of pulse shaping in a multi-frequency NMR tool for reducing the interference between pulse sequences at different RF frequencies. As discussed by *Beard* et al, the excitation and refocusing pulses need not be square waves
15 in the time domain. In the context of the present invention, the teachings of *Beard* et al are also applicable in that the even for a single frequency tool, it is desirable to match the bandwidth of the 90° pulse with the bandwidth of the refocusing pulses.

EXPERT SYSTEM FOR CONTROL OF ACQUISITION PARAMETERS

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[0064] Another novel feature of the present invention is the implementation of an Expert System in the downhole processor for control of the acquisition parameters. There are three types of input data to the expert system. First, the Expert System adjusts the

acquisition parameters from the NMR data alone. In the simplest example the Expert System may compare the QC indicators, such as the sum of echos at different levels. If outliers are detected, a warning signal is sent uphole.

5 [0067] The Expert System analyzes the acquired NMR data and from this, the pulse sequences may be shortened or lengthened (both i and j in eq. (12)) and the τ and TW may be adjusted as discussed above. This may be based upon the determined porosity and T_2 spectrum characteristics such as BVI, BVM (bound water movable), the geometric mean of the T_2 distribution, the main peaks of the T_2 distribution.

10 [0068] The Expert System also has access to measurements made by other sensors described above with reference to Fig. 2. These may relate to drilling conditions or to the formation properties. An example of sensors relating to drilling conditions, i.e., the accelerometer measurements, has already been discussed above with respect to motion
15 triggered pulsing. If the downhole conditions are changing, the acquisition and processing parameters are changed accordingly.

20 [0069] In order to benefit from information relating to formation properties, it is preferable that the other formation evaluation sensors be located between the NMR sensors and the drillbit. With this configuration, measurements made by the other formation evaluation sensors are analyzed downhole and, based upon the rate of penetration, the Expert System knows the properties of the formation being drilled. The FPT gives an estimate of fluid mobility (defined as the ratio of permeability to viscosity).

This, when combined with the NMR-determined permeability gives the fluid viscosity. FPT is also evaluating the fluid type - an information which can be used for NMR MWD again. If the preferred arrangement (other formation evaluation sensors located between the NMR sensors and the drill bit) is not used, then the Expert System changes the NMR acquisition parameters based upon predicted stratigraphy.

[0070] Specifically, gamma rays measurements may be used to determine the shale content of the formation at the depth of the NMR sensors. In a shaly interval, short pulse sequences and small values of τ are sufficient. The presence of hydrocarbons in the formation is diagnosed from resistivity measurements. The presence of gas in the formation may be indicated by acoustic log measurements. As would be known to those versed in the art, even a small amount of gas in the formation significantly lowers the P-wave velocity in a porous sand formation and additional changes in P-wave velocity changes are only slightly affected by the amount of gas present. In such a situation, it is desirable to use a dual wait time acquisition and processing to determine the gas saturation.

[0071] Any changes made by the Expert System in the acquisition and processing parameters are communicated uphole. The operator may then review these changes and, if necessary, override the decisions made by the Expert System.

[0072] The Expert System is preferably implemented using neural networks (NNs). In a preferred embodiment of the invention, more than one NN is used. A first NN is used for

determination of lithology and formation fluid type from formation property measurements. A second NN is used for modifying the NMR acquisition and processing parameters based upon the knowledge of the lithology and fluid type and the drilling conditions. These are discussed separately.

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[0073] The first NN that is used for lithology and fluid determination has as its input measurements from formation evaluation sensors. As noted above, these can include resistivity, acoustic, gamma ray, density and neutron sensors. Based upon these sensor outputs, the lithology and fluid content of the formation can be determined by a human.

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A NN implementation of the lithology/fluid identification involves changing the parameters of the NN to provide a match with the evaluation made by a human expert.

[0074] The second NN that is used in the present invention has its inputs the lithology/fluid content of the formation and the output of drilling condition sensors.

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These inputs are used to modify the NMR acquisition parameters. Once again, the objective is to determine the parameters of this second NN that match those of a human expert.

[0075] As would be known to those versed in the art, there are three main steps involved in using a NN. The first step is the training of the NN. Required for this is a wide statistical sampling of input parameters and the corresponding decision of a human expert. The second step is the validation of the NN; in the validation process, samples that are different from those used in the training process are input to the NN and the

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decision of the NN is again compared with that of the human expert. If there is agreement, then the NN has been validated. Once the NN has been validated, its structure and parameters may be stored in the processor and NN may then be used to process, preferably in real time, measurements made by the logging device. In a preferred embodiment of the invention, the Stuttgart Neural Net Simulator is used for the training of the NN.

[0076] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.